Analysis of Increased Lensing Strength of Substructure in Galaxy Clusters

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ABSTRACT

In 2019, an inconsistency between our observations and our simulations was discovered and published in [1]. We were finding that there were more cases of strong lensing appearing around galaxy cluster substructure than was predicted in simulations. This project is born as an effort to provide reasoning for this unexplained discrepancy.

We begin by looking for cases of gravitational lensing which include a galaxy cluster potential as well as a single galaxy potential which is contained within the cluster. By looking at the resultant Lens Equation and specifying the cases, we find an analytical expression for the behavior of resulting images.

We next apply this expression to both observed and simulated data to look for the best set of parameters to minimize the amount of mass that the single galaxy needs to have the strongest lensing effect.

Finally, we propose an explanation for why, as shown in [1], galaxy cluster substructure has more lensing strength in observations than in simulations. We believe that shallower cluster mass profiles result in stronger lensing potentials for many of the singular galaxies which make up the cluster.

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Background Information

Gravitational Lensing is a natural phenomenon which allows gravity to curve the path along which light travels. This can result in distant objects appearing brighter, dimmer, or to have been multiplied when we observe them. We can describe these images using the **Lens Equation**, which uses an object's source, $\boldsymbol{\beta}$, and the beam of light's deflection angle, $\boldsymbol{\alpha}$, to find the position of its images, $\boldsymbol{\theta}$. The deflection angle itself is calculated using the **lensing potentials** of the nearby masses which affect the image seen.

Lens Equation: $$\vec{\alpha} = \vec{\theta} - \vec{\beta}$$

In 2019, Meneghetti and many others published [1] after spending time with both observed and simulated data on gravitational lensing. They discovered a discrepancy that arose when looking at lensing caused by galaxy clusters. It appeared we see more cases of strong lensing around the singular galaxies which make up the clusters in observation than in simulation.

The purpose of this research project is to provide a reason why we are seeing this inconsistency between observation and simulation.

Research Process

The first step on this project was to familiarize myself with the different variations of gravitational lensing. This was accomplished by reading through [2] and [3], which covered the mathematics and formalisms used on the topic.

Using this knowledge, we continued by trying to develop an expression for the lensing strength of galaxies which are a part of a galaxy cluster. By specifying the parameters of our expression, we found an analytical solution for a specialized, one-dimensional case.

By rearranging this equation to solve for the mass of the lensing galaxy, we were ready to test it on a more general set of cases found in both observed and simulated data. The result of this can be seen in **Figure 1** and **Figure 2**.

The visualization of the masses of these observed and simulated galaxies showed a clear trend of smaller mass galaxies having more lensing strength when inside clusters with shallower mass profiles. We then suggest this as a reason why [1] saw more strong lensing cases from small mass galaxies.

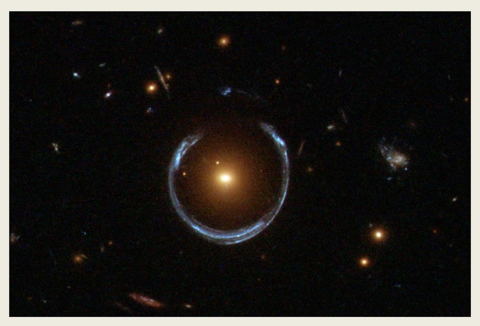

Image 1: An example of gravitational lensing warping the image of a distant galaxy into an **Einstein Ring**

Image 2: Galaxy Cluster MACSJ1206 exhibiting several cases of gravitational lensing

Expressions Used

The very first assumption made in this project was that both the galaxies and galaxy clusters being modelled followed a circularly symmetric variant of an **alphapot potential**, taken from [4] and shown below. Here, $\boldsymbol{\Psi}$ represents the lensing potential, $\boldsymbol{b}$ the normalization constant proportional to the square root of the mass, $\boldsymbol{s}$ the radius of the flat central density, $\boldsymbol{\theta}$ the positions of the lensed images, and $\boldsymbol{\alpha}$ describes the power law exponent of the mass profile.

$$\Psi = b(s^2 + \theta^2)^{\alpha/2}$$

Defining the **Lensing Strength**, ***D***, of an instance of gravitational lensing is done by determining the distance between the most distant images, θ_+ and θ_-. Here, subscripts of 1 denote parameters describing the galaxy cluster, and subscripts of 2 denote parameters describing the individual galaxy. Furthermore, ***R*** is the distance between the center of the cluster and the center of the lensing galaxy.

$$D \equiv \theta_+ - \theta_- = \frac{2b_2}{1 - \alpha_1 b_1 R^{\alpha_1 - 2}(\alpha_1 - 1)}$$

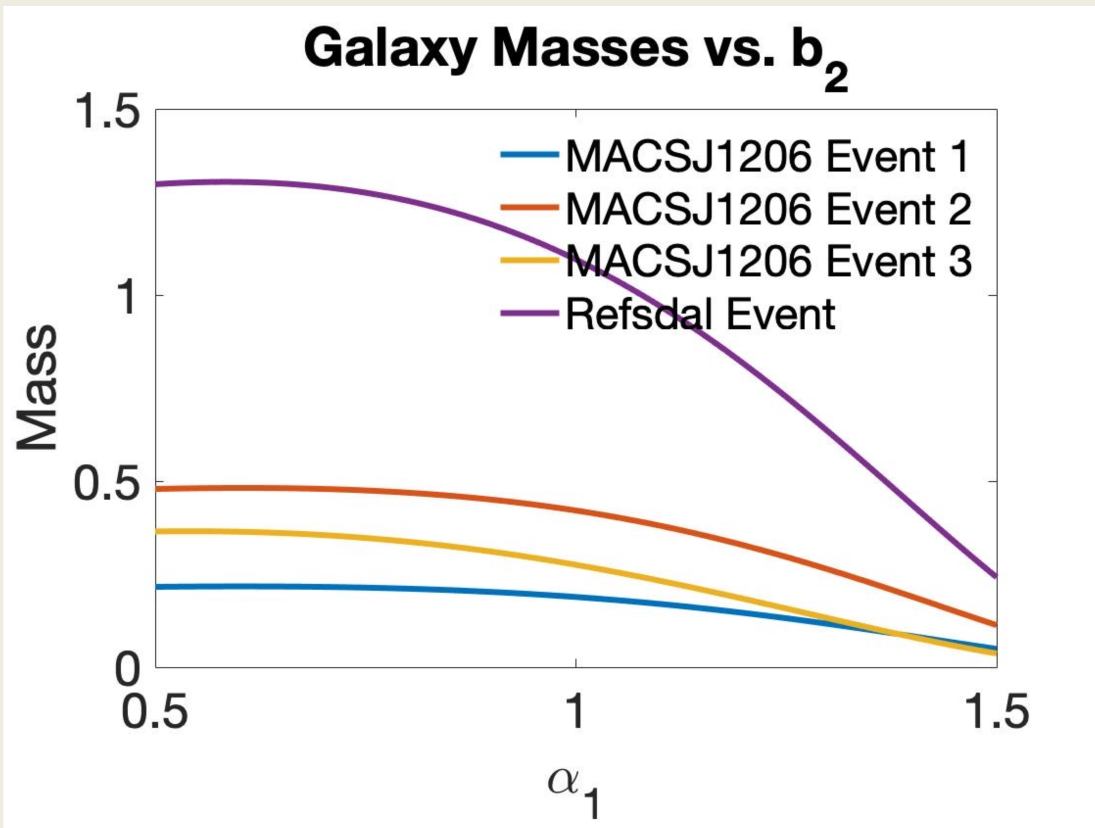

Figure 1. A graph showing the relationship between $\boldsymbol{\alpha}_1$, the mass profile parameter for the host galaxy cluster, and the mass of certain galaxies in galaxy cluster MACSJ1206 as well as a galaxy which was responsible for lensing the Refsdal Supernova. All data shown in this figure was collected from observations.

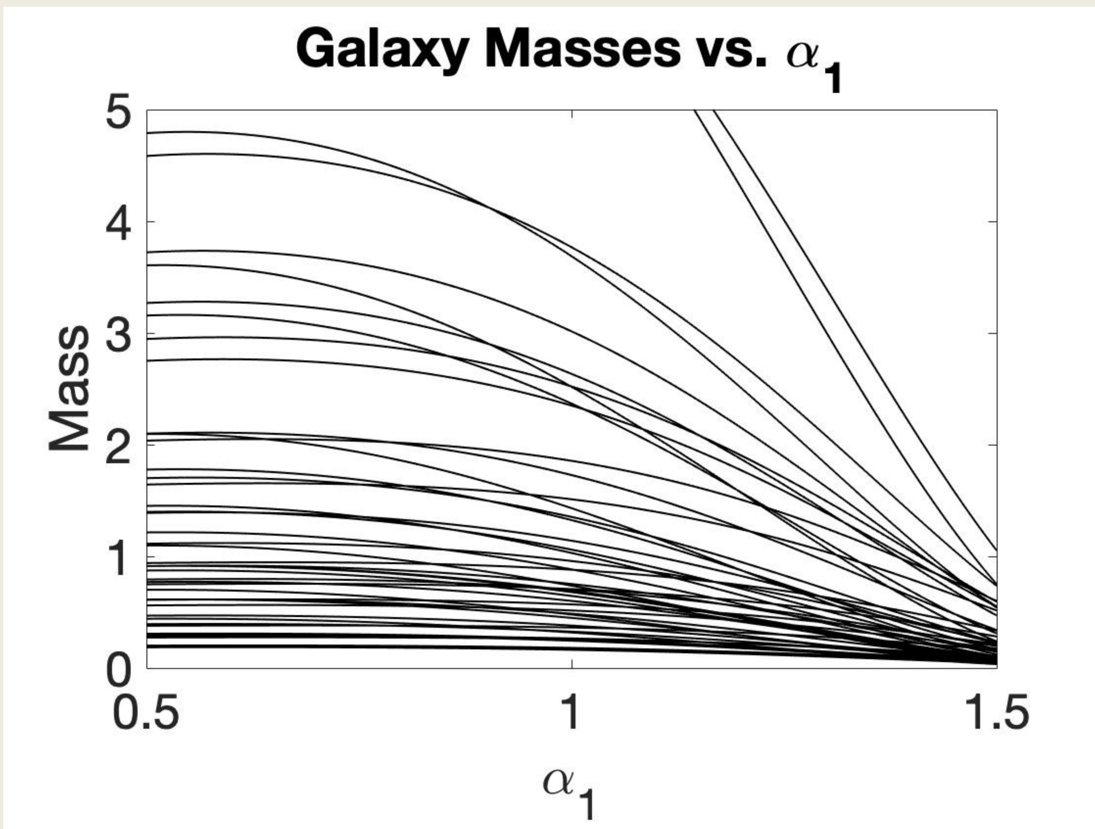

Figure 2. A graph showing the relationship between $\boldsymbol{\alpha}_1$, the mass profile parameter for the host galaxy cluster, and the masses of several of the galaxies which make up the host cluster. All data shown in this figure was collected from a simulated galaxy cluster designed to mimic the mass distribution of galaxy cluster MACSJ1206.

Future Directions

Further avenues of research are available and being pursued.

One branch of research would be to analyze the consequences of assigning shallower mass profiles to these lensing galaxy clusters. If this were to be the case, it might suggest that in these clusters, the dark matter which holds them together appears much more often in the center of the clusters than we initially suspected. The possible implications that arise from this are worthy of investigation, as it could help us to better map the universe around us.

Currently, this project is being continued by looking at new sets of simulated data. We hope to find new methods which can be used to measure the parameters defining the galaxies and host clusters. One of the most promising methods may be found through comparing results with the **Mass Function** of the galaxies which make up the clusters. We hope that this comparison will reveal a specific value of $\boldsymbol{\alpha}_1$ which could be used to measure the lensing potential, and from there, the masses of each lensing galaxy.

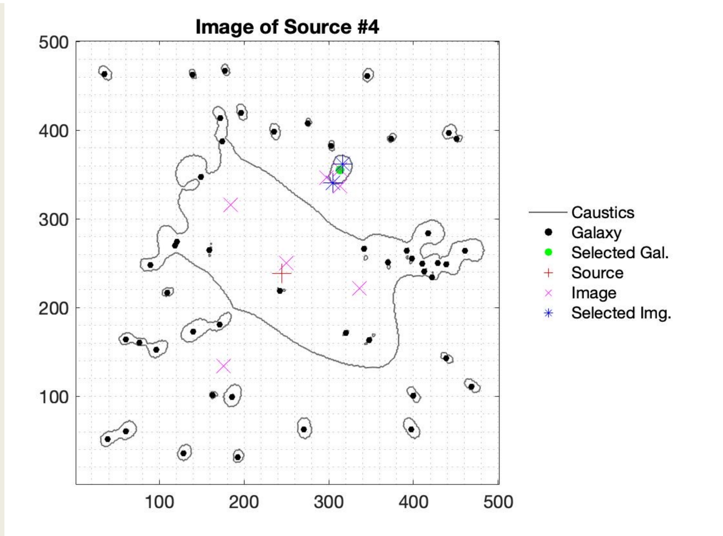

Image 3: An image of the simulated data being worked on for the continuation of this project

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